Army Research Laboratory

A Fuel Consumption Algorithm for Unmanned Aircraft Systems

by Terry Jameson

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14. ABSTRACT

The Army Research Laboratory, Battlefield Environment Division has been developing an Aviation Weather Routing Tool (AWRT) to address the issue of weather impacts upon various Unmanned Aircraft System (UAS) missions. The AWRT depicts regions of adverse weather impacts and then searches for alternate routes that minimize those impacts. A related factor that has yet to be included in AWRT involves UAS fuel consumption. Fuel consumption rates, remaining fuel quantity, and therefore allowable times' on-target are vital issues that must be considered to safely and most effectively employ UAS in their various mission roles. In particular, as AWRT proposes alternate routes that minimize adverse weather effects, additional fuel requirements to fly those routes must be taken into account. We have developed a prototype Fuel Consumption Algorithm (FCA) that addresses some of these issues. The prototype FCA has been designed such that minimal operator input is required, while a maximum amount of pertinent flight information is produced. UAS flight performance characteristics, prevailing winds, and mission route definitions are incorporated into the FCA. Using these data, the algorithm computes ground speeds along the various mission segments (and therefore flying times), fuel consumed, and then fuel and time available to be expended at a target area.

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1. Introduction

Unmanned Aircraft Systems (UAS) have become a key component of U.S. military operations in theaters abroad, and are rapidly finding their place in border patrol and other homeland security and law enforcement missions within the Continental United States. UAS are likely to have an ever-increasing role in reconnaissance, surveillance, communications, and combat in the near future.

The Army Research Laboratory, Battlefield Environment Division (ARL-BE) has been developing an Aviation Weather Routing Tool (AWRT) to address the issue of weather impacts upon various UAS missions. The AWRT depicts regions of adverse weather impacts on a map background display and then searches for alternate routes that minimize those impacts. Additional details about the concept behind AWRT and how it functions are presented in section 2.

A related factor that has yet to be included in AWRT involves UAS fuel consumption. Fuel consumption rates, remaining fuel quantity, and therefore allowable times' on-target are vital issues that must be considered to safely and most effectively employ UAS in their various mission roles. In particular, as AWRT proposes alternate routes that minimize adverse weather effects, additional fuel requirements to fly those routes must be taken into account.

We have developed a prototype Fuel Consumption Algorithm (FCA) that addresses some of these issues. The prototype FCA has been designed such that minimal operator input is required, while a maximum amount of pertinent flight information is produced. UAS flight performance characteristics, prevailing winds, and mission route definitions are incorporated into the FCA. Using these data, the algorithm computes ground speeds along the various mission segments (and therefore flying times), fuel consumed, and then fuel/time available to be expended at a target area.

Future work on the FCA will focus on adding more detailed UAS aerodynamic factors into its algorithm and expanding its capabilities to accommodate more complicated missions. It will also be rewritten in the JAVA programming language (the prototype is written in MATLAB code, explained in the section 4.) in order to facilitate its incorporation into AWRT. It is hoped that the FCA will ultimately prove to be a valuable decision aid for UAS mission commanders.

2. Background

2.1 UAS Fuel Consumption Issues

There are several factors affecting UAS fuel consumption, that do not normally apply to manned aircraft, and that can have significant impacts on their missions. These include:

- UAS have slower airspeeds than most manned aircraft, and as such are more susceptible to the effects of the wind.
- Many UAS are required to return to their launch/recovery (LR) point, and alternate landing sites are seldom an option.
- Frequently there is a requirement to maximize time-on-target(s) before returning to the LR point. Fuel management and optimized utilization are almost always critical issues.
- In many cases, a UAS mission commander (MC) will be asked to divert the aircraft from its primary target area (the one for which the flight was originally planned) to secondary area(s), while the mission is underway.

The factors listed above have been described to ARL-BE by instructors at the UAS Training Facility, Ft. Huachuca, AZ, and by UAS MCs of the Customs and Border Protection, Air and Marine Operations facilities in Sierra Vista, AZ, and Riverside, CA (personal communication, June and August, 2008, respectively).

2.2 Aviation Weather Routing Tool

The AWRT promises to be a powerful tool in the hands of the MC. It performs a number of tasks to reduce the decision-making load on UAS operators, including:

- Merging a forecast model 3-D weather data grid with weather impact critical threshold values to create a weather effects data cube.
- Depicting areas of adverse, marginal, or no-impact weather from the weather effects data cube on a map display grid as areas of red, amber, or green shading, respectively.
- Producing a highly-intuitive depiction of areas of, and reasons for, adverse weather conditions, relative to planned/desired UAS routes to target.
- Invoking a path-search algorithm to determine alternate route(s) to minimize weather effects/risks. The path-search algorithm is called “A*” (pronounced “A-star”) and is commonly used in computer gaming applications to route characters around a screen and in the communications industry to model and optimize the routing of messages through a communications grid. A tutorial on A* may be found at the following link:

http://www.policyalmanac.org/games/aStarTutorial.htm[1]

As mentioned above, a valuable add-on to AWRT would be an easy-to-use, highly-automated algorithm embedded within the routing tool that quickly recalculates fuel requirements as alternate routes are generated to complete the mission and return to base – maximizing safe time-on-target(s).

3. Approach

The approach taken in this research effort has been to develop a prototype fuel-consumption algorithm that will compute the following: course, wind correction angle, heading, ground speed, fuel consumed, and available fuel and time on secondary target(s). An emphasis has been placed on minimizing required operator input to be limited to:

- Launch point and target point(s) coordinates.
- Initial flight altitude.
- UAS designation (so that the FCA retrieves UAS-specific information from an embedded data file).
- Periodic input of forecast or UAS-observed winds. The UAS-observed winds are defined in Section IV.

4. Definitions

The following definitions are required in order to understand the operation of the FCA.

(1) Vector: Herein, a vector magnitude alone is bracketed by solid vertical lines. For example, the magnitude of Vector "A" is indicated by |A|. A bold-font arrow above the letter indicates the vector itself (both magnitude and direction).

(2) The word "True" associated with a course or heading indicates a value measured in compass degrees relative to True North. This distinction is made to differentiate from *Magnetic* courses and headings which are used in flight navigation but are not pertinent to the FCA discussion herein.

(3) True Course (TC): Flight path relative to the ground.

[1] A* Path finding for Beginners (accessed April 20, 2009).

(4) True Heading (TH): Direction of the longitudinal axis of the aircraft; the direction the aircraft is "pointing" in order to compensate for wind drift and maintain the desired TC.

(5) TC Vector: The vector for which the directional orientation is the TC and for which the length is proportional to the Ground Speed (GS) defined below. The directional orientation of the TC Vector is an initially *known* value.

(6) GS: Speed of the aircraft *relative to the ground*. GS is a function of the summation of the TH and the Wind Vectors. The length of the TC vector is proportional to the GS. The GS is initially *unknown* and is the primary value to be determined for each mission leg; in order to most accurately assess fuel consumption, remaining fuel and therefore, allowable mission time.

(7) TH Vector: The vector for which the directional orientation is the TH and for which the length is proportional to the True Air Speed (defined below). The directional orientation of the TH Vector is an initially *unknown* quantity.

(8) True Airspeed (TAS): Speed of the aircraft *relative to the air*. TAS is a function of the thrust being developed by the engine(s)/propeller(s) and being opposed by the total amount of drag created by the UAS airframe and sensor attachments. The length of the TH vector is proportional to the TAS and is an initially *known* quantity.

(9) Wind Vector (W): Either the *forecast* wind direction/speed (FWD/FWS) provided by Numerical Weather Prediction (NWP) computer forecast models or the wind derived by the UAS Global Positioning System (GPS) and therefore *observed* by the UAS (OWD/OWS). Both the directional orientation and length of the Wind Vector (whether forecast or observed) are initially *known* quantities.

(10) Wind Correction Angle (WCA): Directional difference between the TC and TH vectors. Since the directional orientation of the TH Vector is initially *unknown*, so too is the value of the WCA. This is the amount of correction the UAS operator (or the vehicle's automated guidance system) must apply via the TH to maintain the desired path over the ground (the TC).

(11) Supplementary Angle (Supp_Ang): Either of two angles that, when added together, produce an angle of 180 deg. Thus, when an angle is known, its supplementary counterpart may be found by subtracting it from 180.

(12) MATLAB: The MATrix LABoratory programming language. The prototype fuel consumption program and its subprograms were developed in MATLAB. Programs written in MATLAB contain a ".m" file extension; e.g. "file_name.m".

(13) Launch/Recovery Point (LR): Since most UAS must return to their launch point in order to land (or be "recovered" by whatever means applicable to a particular aircraft), the distinction is made herein to call this location the "LR" point.

5. The TC-TH-W Vector Triangle

The vector sum of the TH and W vectors ("tip-to-tail" alignment of the two vectors) results in the TC vector. The triangle shown in figure 1 comprised of these three vectors is the "TC-TH-W Vector Triangle".

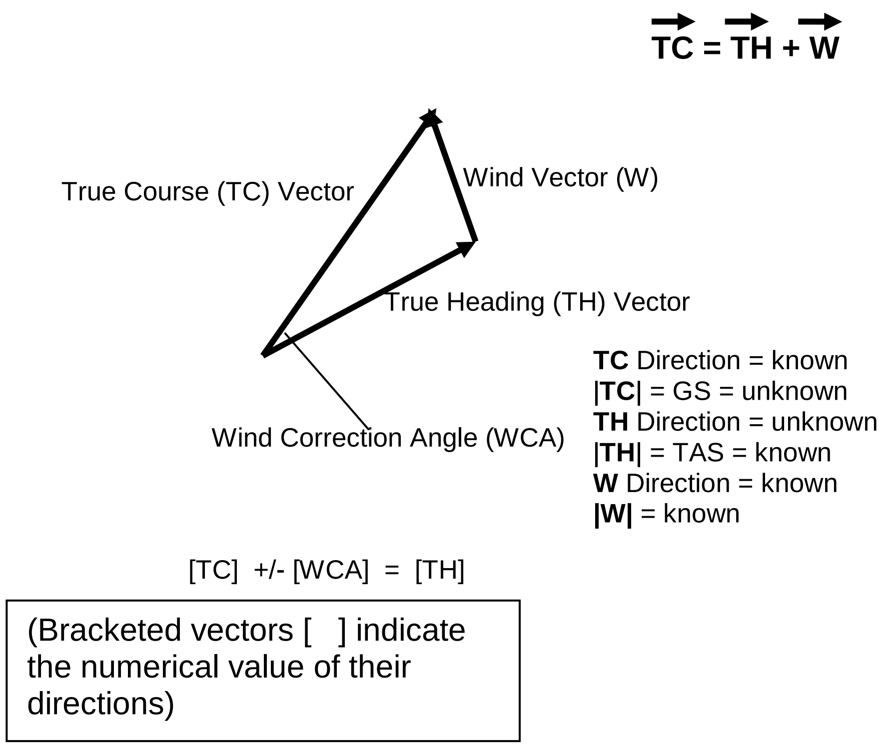

Figure 1. The TC-TH-W Vector Triangle.

As described above, some of the directions and magnitudes of these vectors are known while others are unknown and must be solved for using trigonometric relationships.

6. Coordinate System

The coordinate system referred to herein and being employed by the FCA is the Universal Transverse Mercator (UTM) coordinate system (hereafter simply called the "UTM"). The UTM is based upon an X/Y grid (East-West/North-South, respectively) in which coordinates are measured in meters, all with positive values. Coordinate values increase when moving from West to East and from South to North. The UTM was selected since the FCA's trigonometric relationships require an X/Y coordinate system and since it should seamlessly transfer over to any X/Y grid-based military system. The UTM naming convention used throughout this document is as follows:

- Route segment start point is designated as "1", end point as "2"
- UTM "X" coordinate is designated as UTM_X; "Y" coordinate is designated as "UTM_Y"
- Start point: UTM_X_1, UTM_Y_1; End point: UTM_X_2, UTM_Y_2

Motion in the UTM is designated as follows:

- "U" and "V" values are used for speeds in X and Y axes, respectively
- +U = motion from West to East, +V = motion from South to North

More information on the UTM coordinate system can be found at the following Web site:

http://www.uwgb.edu/dutchs/FieldMethods/UTMSystem.htm[2]

The locations of the LR and target areas that will be introduced in Section XV were taken from a civilian aeronautical chart where they are given in latitude/longitude (lat/lon) degrees. For the purpose of this study, it was necessary to convert the lat/lon coordinates to UTM coordinates. A link at the UTM Web site (provided below) opens an Excel spreadsheet that makes these conversions for the user.

http://www.uwgb.edu/dutchs/UsefulData/UTMFormulas.htm#Spreadsheet[3]

7. Angle Notations and Calculations

- Capital letters indicate an angle; lowercase letters indicate the length of the side of the triangle opposite to the angle. For example, the length of the side opposite from "Angle A" is indicated by a lower-case letter (i.e., "a").
- The magnitude of an angle is denoted by enclosing the designator in square brackets, for example, the magnitude of the WD angle would be denoted by [WD].

In some cases, the *absolute values* of the difference between angles are used. For example, (ABS ([TC]-[OWD]), meaning the absolute value of the difference between the TC angle and the angle of the observed wind direction. Using absolute values is done to prevent obtaining negative values for the difference.

[2] The Universal Transverse Mercator System (accessed April 20, 2009).

[3] Converting UTM to Latitude and Longitude (Or Vise Versa) (accessed April 20, 2009).

The sign (positive or negative) for some angles is retained, for example, the WCA. In this way, the WCA can be added to the TC in order to obtain the correct TH.

8. True Course (TC) Computations

The following steps are taken to find a TC along a particular route segment:

- Find distance displacements along a route segment in the X and Y axes. Subtract route segment START point UTM coordinates *FROM* the END point UTM coordinates to have correct sign convention:
    - DEL_X = UTM_X_2 minus UTM_X_1
    - DEL_Y = UTM_Y_2 minus UTM_Y_1
- Find distance "S" along segment with Pythagorean Theorem:
    - $S = \sqrt{(DEL\_X)^2 + (DEL\_Y)^2}$

An example of these computations is shown in figure 2.

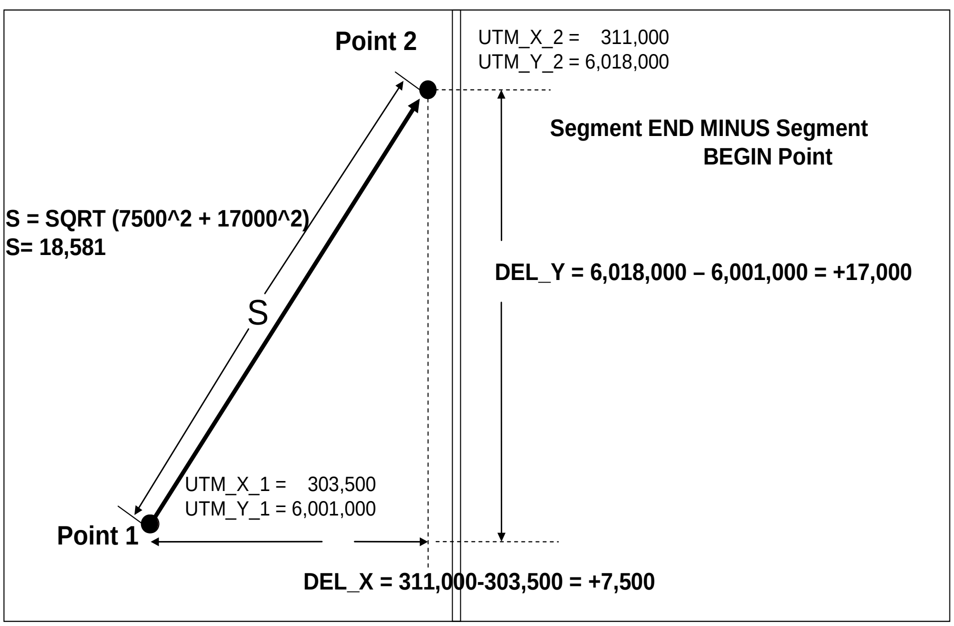

Figure 2. X-axis and Y-axis displacements and route segment distance computations.

- Find direction FROM WHICH the UAS is coming, along this route segment, called "D":

$$D = 270 - (\text{atan2}(DEL\_Y, DEL\_X))$$

Where "atan2" is the Inverse Tangent or Arc Tangent function in MATLAB and Excel, for example. The answer "D" is in radians, for which a conversion to degrees is required. The equation for “D” works correctly regardless of the quadrant from which the UAS is coming, as long as “DEL_Y” and “DEL_X” have the correct signs.

- Find the opposite direction, called the Down Wind Direction (DWD), which is the direction TOWARD WHICH the UAS is going; do so by adding 180° to “D”:

$$\text{DWD} = \text{D} + 180°$$

The DWD is equivalent to the TC.

- Check if the TC is greater than 360°. If so, subtract 360 to find the actual TC.

An example of a TC computation is shown in figure 3.

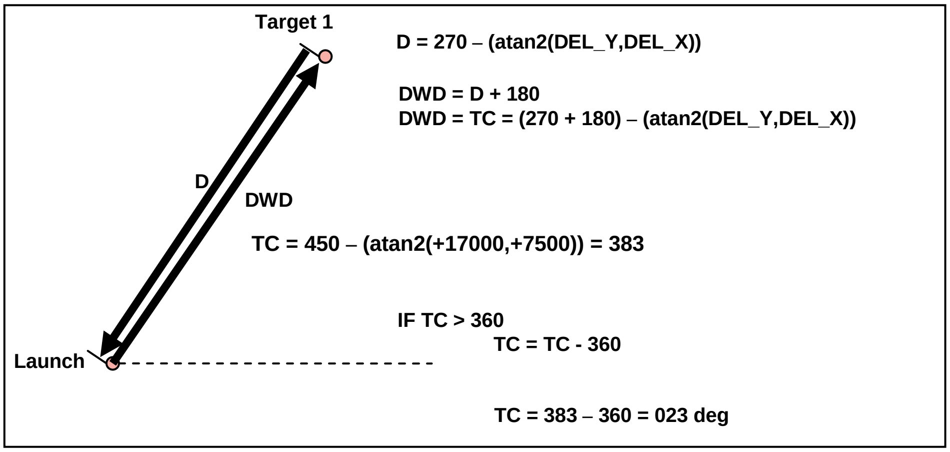

Figure 3. True Course computation.

9. Wind Correction Angle (WCA) Calculation

The steps to be followed to determine the WCA along a generic route segment are listed below and illustrated in figure 4.

- Subtract the TC direction (or angle, named here the “[TC]”) from the observed or forecast wind direction (named here the “[WD]”), to find the angle supplementary to “Angle A” (see figure 4). This angle is named “[Supp_Ang]”

- Subtract “[Supp_Ang]” from 180 to obtain “Angle A”

- Use the “Law-of-Sines”[4] ratio to compute the value of “Angle B”: $\dfrac{a}{\sin A} = \dfrac{b}{\sin B}$

[4] Washington, A.J. *Basic Technical mathematics with Calculus*, 8th ed.; Pearson, Addison, Wesley: Boston, MA, 2005; p. 278.

To do so, solve the Law-of-Sines for “Angle B”: $B = \sin^{-1}\left[\frac{b * \sin A}{a}\right]$

- According to the TC-TH-W triangle in figure 4, side “a” is the TAS, an initially known value. Side “b” is the wind speed, also an initially known value. “Angle A” has now been derived (above) and is known value. Thus the value of “Angle B” can be obtained.
- “Angle B” is the WCA

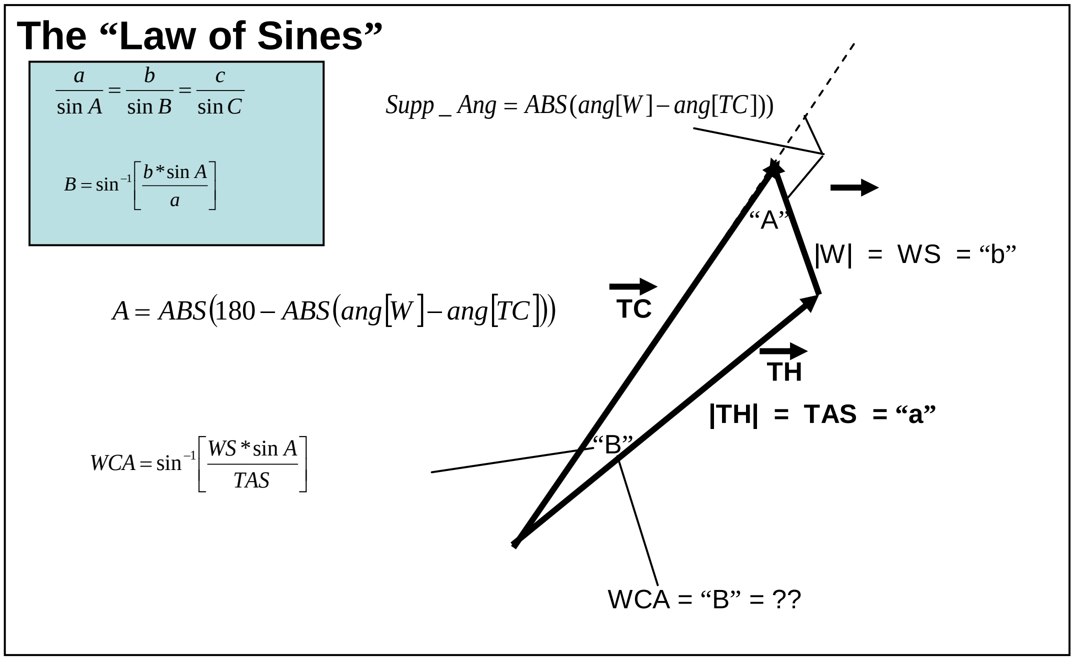

Figure 4. Vector diagram for the WCA calculation.

10. Ground Speed (GS) Calculation

The following steps are taken in the FCA to solve for the route segment GS. Figure 5 is an illustration of this process:

- Employ the Law-of-Sines once again, this time solving for “c”, which is the magnitude of the TC vector and equals the GS.
- The value of “Angle C” is found using the trigonometric relationship that the sum of angles in a triangle equals 180°. Angles A and B are known from the previous WCA computation. So,

$$[C] = 180 - ([A] + [B])$$

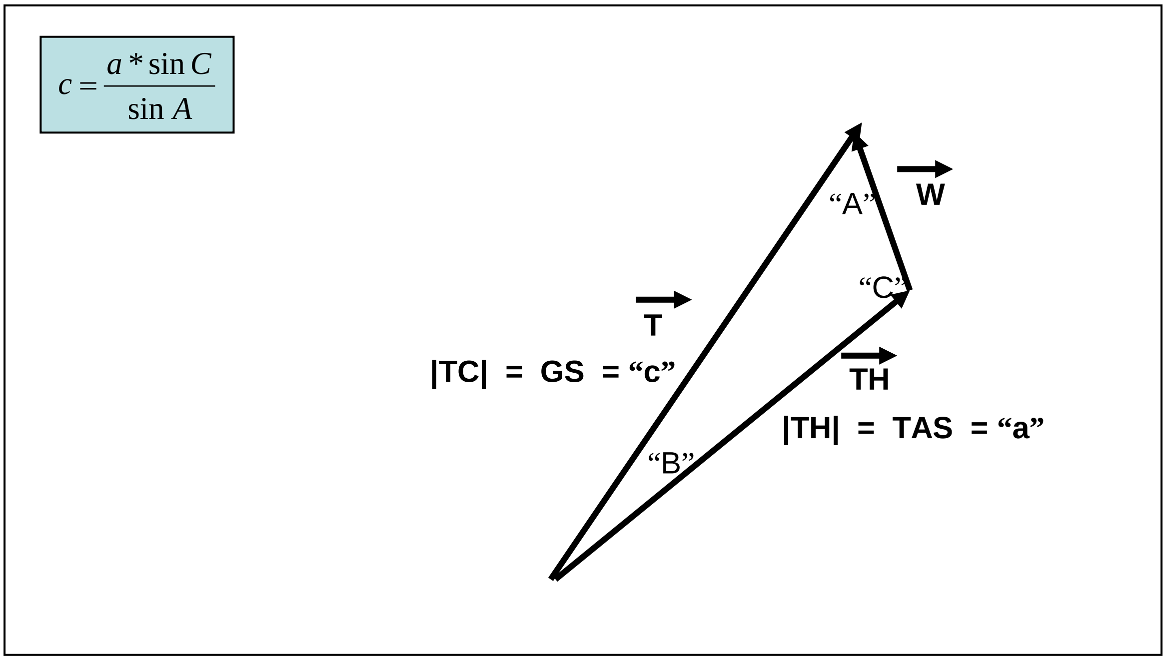

Figure 5. Ground speed calculation.

11. UAS Input File

Each run of the FCA requires the input of a UAS’s-specific data file that includes:

- True Air Speed (kts)
- Fuel Capacity (gal)
- Fuel Consumption Rate (gal/hr), for:
  - Climb out
  - Cruise
  - Loiter
- Rate-of-climb (ft/min)
- Required fuel reserve (in hours of flying time remaining) upon return to base

12. Mission Coordinates Input File

Each run of the fuel consumption program requires the input of a mission coordinates data file that includes:

- UTM_X coordinate of the LR point (m) (named UTM_X_LR)
- UTM_Y coordinate of LR point (m) (named UTM_Y_LR)
- LR Point field elevation (m Above Sea Level [ASL])
- UTM_X coordinate of Target 1 (m) (named UTM_X_T1)
- UTM_Y coordinate of Target 1 (m) (named UTM_Y_T1)

13. Fuel-Consumption Program Overview

The prototype MATLAB program developed for the FCA is named **"Fuel_Con.m"**. This program computes fuel consumed on an "out and back" mission to a single target area, or on a three-legged flight path with a primary and a secondary target area. The **"Fuel_Con.m"** program has four associated subroutine programs:

13.1 True_Course.m

Computes the TC along a route segment between Point 1 and Point 2 (start and end points of the segment, respectively). Input to the subprogram call is:

- UTM_X_1
- UTM_Y_1
- UTM_X_2
- UTM_Y_2

Output returned to the main program is:

- TC from segment Point 1 to Point 2 (called "TC_1_2")
- Distance along the route segment

13.2 Wind_Cor_Ang.m

Computes the WCA along a route segment. Input to the subprogram call is:

- Wind Direction (observed or forecast)
- Wind Speed (observed or forecast)
- TC_1_2

Output returned to the main program is:

- WCA for segment Point 1 to Point 2 (called "WCA_1_2")
- Optionally, two other internal angles can be output for program diagnostic purposes

13.3 Gnd_Spd.m

Computes the GS along a route segment. Input to the subprogram call is:

- Wind Speed (observed or forecast)
- WCA

Output returned to the main program is:

- GS from segment Point 1 to Point 2 (called "GS_1_2")

13.4 Sgmt_fuel.m

Computes the fuel consumed along all segments of the mission. Input to the subprogram call is:

- Length of each mission segment (meters)
- GS along each mission segment (m/s)
- Fuel consumption rate (cruise, gal/hr)

Output returned to the main program is:

- Time required to fly each mission segment
- Fuel required to fly each mission segment

14. Fuel-Consumption Program Execution Outline

The following outline delineates the flow of program execution of "**Fuel_Con.m**". The section and subsection numbers in the outline correspond to those in the comments of the program itself.

0.0 Constants Definition
1.0 Input and Output File Opening
    1.1 Input files opening (UAS Performance File and Mission Coordinate File)
    1.2 Output File Opening

2.0 Parameter and Data Input
    2.1 Read UAS-specific performance & mission coordinates parameters (from input files)
    2.2 Input initial cruise altitude (manual entry)
    2.3 Input Target 1 planned loitering time (manual entry)
    2.4 Secondary Target Definition
        2.4.1 Option of no secondary target (T2). Manual entry of “Option 1”. Set T2 coordinates equal to T1.
        2.4.2 Option of secondary target (T2). Manual entry of “Option 2”. Input T2 coordinates (UTM meters) (manual entry).
3.0 Compute Non-varying Fuel Consumption Parameters
    3.1 Determine climb-out time
    3.2 Compute projected fuel consumption at T1
    3.3 Compute required fuel reserve arriving back at LR
4.0 True Course (TC) and Mission Segment Length Computations
    4.1 TC and distance LR to T1 (TC_LR_T1, DIST_LR_T1)
    4.2 TC and distance T1 to T2 (TC_T1_T2, DIST_T1_T2)
    4.3 TC and distance T2 to LR (TC_T2_LR, DIST_T2_LR)
5.0 Initial Forecast Wind Input (Planning Phase)
    5.1 Input Forecast Wind Direction/Speed (deg/kts)
    5.2 Equate the Forecast Wind Direction/Speed to the generic WD/WS parameters
6.0 Wind Correction Angle (WCA) Computations – Forecast Winds Input
    6.1 WCA LR to T1
    6.2 WCA T1 to T2
    6.3 WCA T2 to LR
7.0 Ground Speed (GS) Computations – Forecast Winds Input
    7.1 GS LR to T1
    7.2 GS T1 to T2
    7.3 GS T2 to LR
8.0 Call fuel compute function to find fuel used along three route segments
9.0 Determine the allowable time-on-station at T2
    9.1 Determine the available fuel at T2
    9.2 Given T2 fuel, determine the allowable mission time at T2
10.0 Write all data (including interim diagnostics) to output file
11.0 Observed wind input section (manual input). (Observed winds LR to T1)
12.0 Compute the WCA’s for the three route segments using the new winds.
13.0 Compute the GS’s for the three route segments using the new winds.
14.0 Compute the fuel consumed for the three route segments using the new winds.
15.0 Compute the fuel and time available at T2 using the new winds.
16.0 Write the new fuel and time available at T2.

17.0 Input the ACTUAL times spent en route from LR to T1 and at T1 (manual input).
   17.1 Compute ACTUAL fuel expended en route to T1 and at T1.
18.0 Observed wind input section (manual input). (Observed winds leaving T1 for T2)
19.0 Compute the WCA's for the TWO, remaining route segments (T1 to T2 and T2 back to L/R) using the new winds.
20.0 Compute the GS's for the TWO, remaining route segments using the new winds.
21.0 Compute the fuel consumed for the TWO, remaining route segments using the new winds.
22.0 Compute the fuel and time available at T2 using the new winds. ACTUAL fuel consumed from LR to T1 and at T1are used in this computation.
23.0 Write the new fuel and time available at T2.
24.0 Input the ACTUAL time spent en route from T1 to T2 (manual input).
   24.1 Compute ACTUAL fuel expended en route from T1 to T2.
25.0 Observed wind input section (manual input). (Observed winds arriving at T2)
26.0 Compute the WCA for the ONE, remaining route segment (T2 back to L/R) using the new winds.
27.0 Compute the GS for the ONE, remaining route segment using the new winds.
28.0 Compute the fuel consumed for the ONE, remaining route segment using the new winds.
29.0 Compute the fuel and time available at T2 using the new winds. ACTUAL fuels consumed from L/R to T1, at T1 and from T1 to T2 are used in this computation.
30.0 Write the new fuel and time available at T2.

15. Fuel-Consumption Program Testing

The FCA prototype, **fuel_con.m**, has been extensively tested for accuracy. A test scenario was developed for a hypothetical UAS mission within the state of New Mexico (NM). A triangular-shaped route was established between three points; those located at the Las Cruces, NM airport (International Air Transport Association [IATA] location indicator "LRU"), the Navaho Lake, NM airport (IATA location indicator "1V0"), and the Clayton, NM airport (IATA location indicator "CAO"). LRU was considered to be the LR point, 1V0 the "T1" and CAO the "T2". This hypothetical UAS mission route was hand-plotted on an aeronautical chart (NM Aeronautical Chart, NM Aviation Division, Santa Fe, NM, 2005), and the lat/lon coordinates of the LR point and target areas were obtained from the chart's airport directory. The lat/lon airport coordinates were converted to UTM using the Excel spreadsheet described in section 6 of this document.

15.1 True_Course.m

The "True_Course.m" subprogram was tested for the triangle-shaped route described above in section 15. The UTM coordinates for the three points are depicted in figure 6. Also, the TC values and the distances for the three route segments, as calculated by the subprogram, are illustrated. As an example, the actual computation of the TC and distance for the LR to T1 segment is shown below the figure.

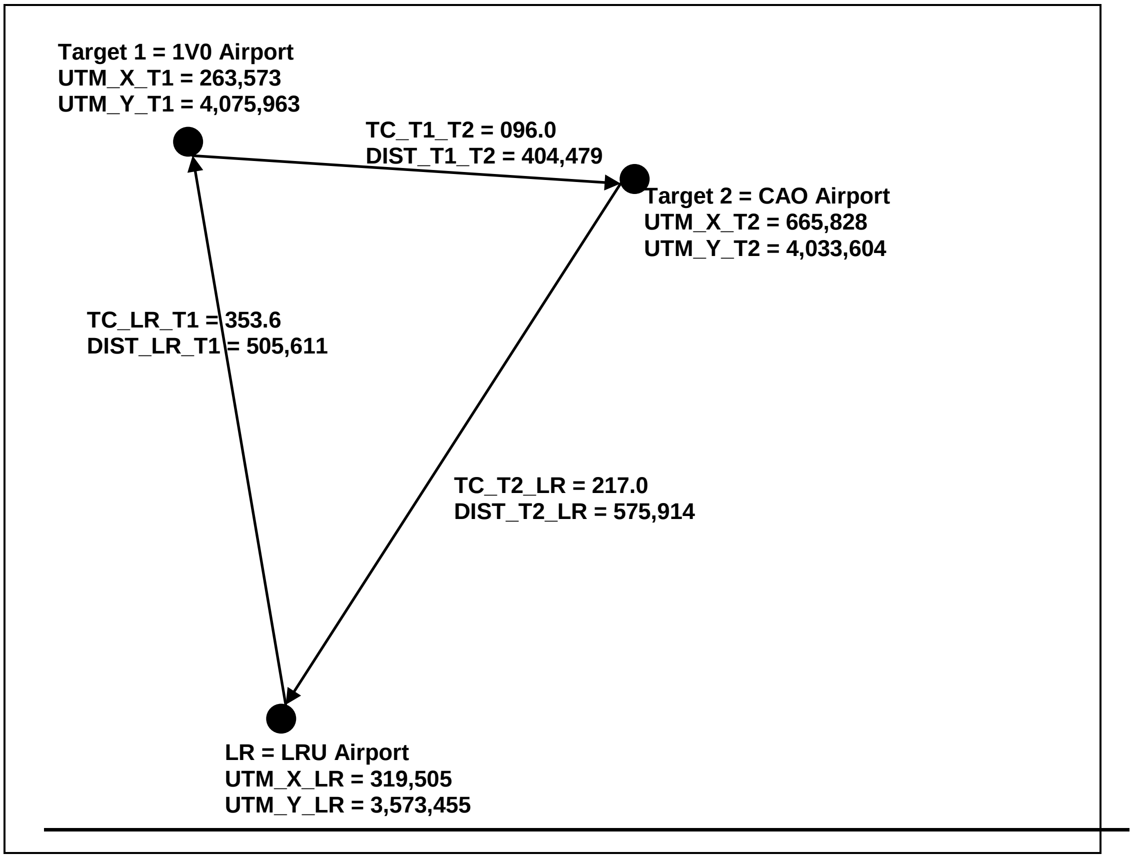

Figure 6. Triangular-shaped Test Mission Scenario.

DEL_Y_LR_T1 = 4,075,963 – 3,573,455 = 502,508 m

DEL_X_LR_T1 = 263,573 – 319,505 = -55,932 m

D = 270 – atan(DEL_Y_LR_T1, DEL_X_LR_T1) = 173.6 deg

DWD = d + 180 = 353.6 deg

DIST_1_2 = DIST_LR_T1 = sqrt (502,508^2 + 55932^2) = 505,611 m

Similar computations were performed for the other two segments of the route. The courses and distances were then measured manually on the aeronautical chart, confirming that all output values from the “True_Course.m” subprogram were correct.

15.2 Graph paper construction of a True Course (TC), True Heading (TH), Wind (W) vector diagram

TC-TH-W vector diagrams constructed on graph paper have been used to verify the accuracy of the FCA. The foundation of these diagrams is based upon the following relationship between the TC, the TH, and the W vectors:

(1) TC = TH + W   or, (2) TH = TC - W

Procedure:

1. Select a speed scale on the graph paper such that the width of the sheet is no less than approximately 100 m/sec. This scale will allow typical true air speeds, ground speeds and wind speeds encountered in UAS fuel consumption calculations to be depicted as a vector diagram on a single sheet.

2. Using a protractor, draw a long line oriented in the direction of the TC. The angular orientation of this line is known, it being the TC. The length of the TC vector is not yet known, it being proportional to the GS.

3. Pick an ending point on this TC line. This point will become the tip of the TC vector.

4. Using a protractor and ruler, draw a wind speed/direction vector (W) with its <u>tip</u> at the <u>tip</u> of the TC vector. Both the length of the W vector (the wind speed), and its orientation (the wind direction) are known. The length of this vector then is proportional to the wind speed and its orientation represents the wind direction. So far, the diagram represents equation 2 above; a vector subtraction of the wind from the TC. Their difference is the TH vector. However, at this point the length of the TC vector is still not known.

Note: The length of the TH vector is known, it being the True Air Speed (TAS). Its orientation, however, is still not known.

5. Use a compass to draw an arc, centered at the <u>tail</u> of the W vector. The radius of the arc is the TAS according to the pre-selected length scale. Mark the point where this arc intersects the TC line. The point of intersection is the <u>tail</u> of both the TC and the TH vectors.

6. The resulting vector triangle represents equation 1; a vector addition of the TH vector and the W vector, to obtain the TC vector.

7. The angle between the TC and the TH vectors is the Wind Correction Angle (WCA). The length of the TC vector is the GS.

15.3 Wnd_Cor_Ang.m

The “Wnd_Cor_Ang.m” MATLAB subprogram was evaluated to ensure the correct computation and each wind input of the WCAs along each route segment. Figure 7 illustrates the TC-TH-W vector diagram for the LR-to-T1 segment and for which a forecast wind of 120 deg/20 kts (10.3 ms^{-1}) was assumed. The equations below the figure outline the individual steps involved.

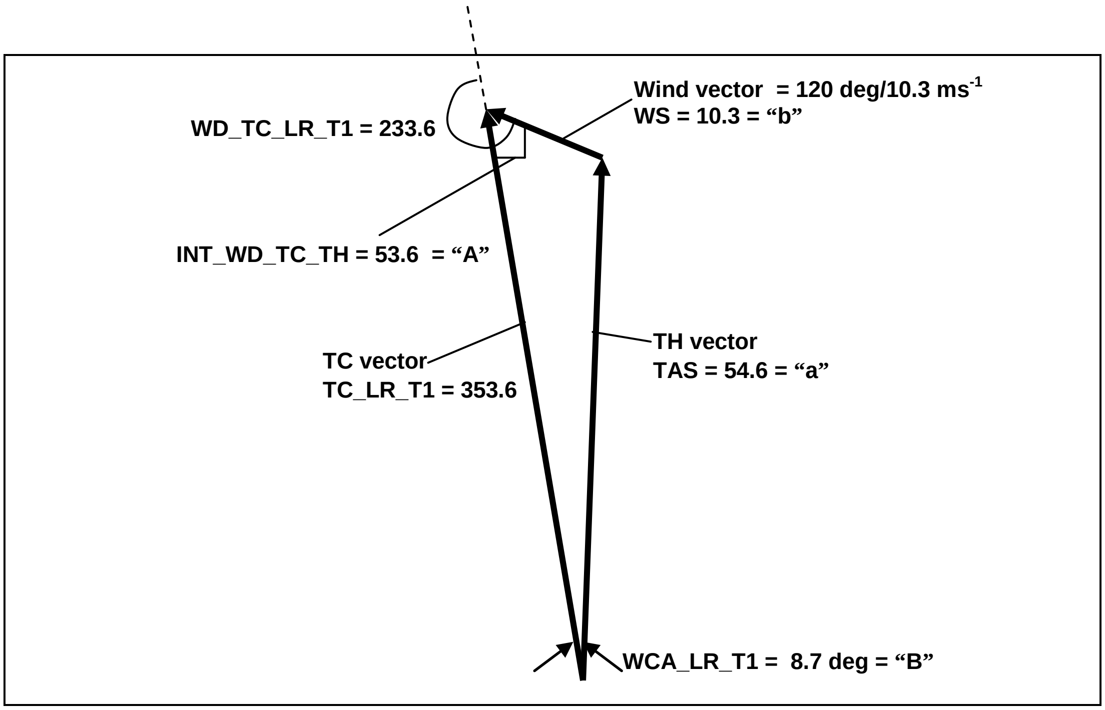

Figure 7. WCA computation example.

WD_TC_LR_T1 = ABS (|WD| – |TC|) = ABS(120 - 353.6) = 233.6

INT_WD_TC_TH = ABS(180- |WD_TC_LR_T1|) = ABS (180-233.6) = 53.6

$$B = \arcsin\left(\frac{b * \sin A}{a}\right)$$

$$WCA = \arcsin\left(\frac{WS * \sin(INT\_WD\_TC\_TH)}{TAS}\right)$$

$$WCA = \arcsin\left(\frac{10.3 * \sin(53.6)}{54.6}\right) = 8.7\,\mathrm{deg}$$

15.4 Gnd_Spd.m

The "Gnd_Spd.m" MATLAB subprogram was evaluated to ensure the correct computation of the GS's along each route segment and for each wind input. Figure 8 illustrates the TC-TH-W vector diagram for the LR-to-T1 segment and for which the WCA of 8.7 deg is now known. The equations below the figure outline the individual steps involved.

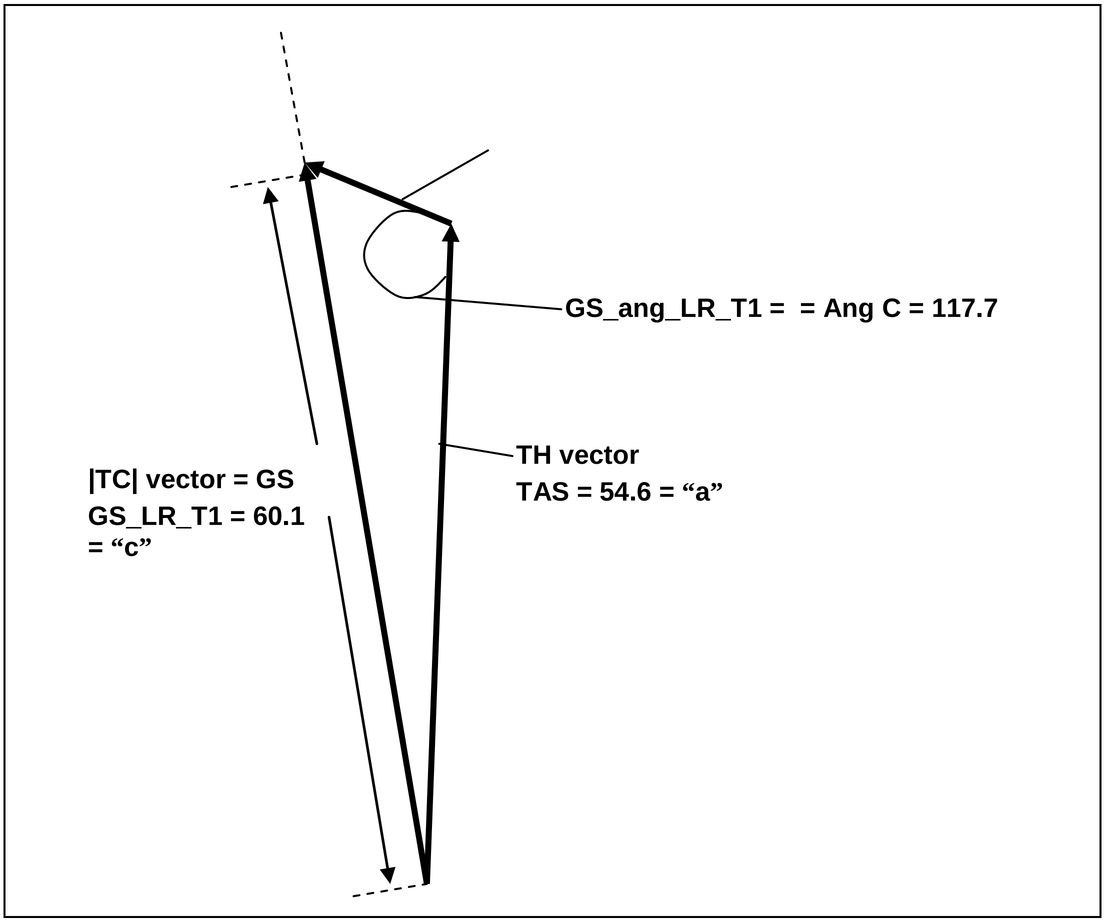

Figure 8. GS computation example.

GS_ang_LR_T1 = 180 - (INT_WD_TC_TH + WCA L_T1) = 180(53.6 + 8.7) = 117.7

$$c = \frac{a * \sin C}{\sin A}$$

$$GS\_LR\_T1 = \frac{TAS * \sin(GS\_ang\_L\_T1)}{\sin(INT\_WD\_TC\_TH)}$$

$$GS\_LR\_T1 = \frac{54.6 * \sin(117.7)}{\sin(53.6)} = 60.1 m/s$$

Figure 9 is the actual hand-plot of this particular TC-TH-W vector diagram (as described in section 15.2) which was drawn to verify the accuracy of “Wnd_Cor_Ang.m” and “Gnd_Spd.m” for the LR-to-T1segment of the mission.

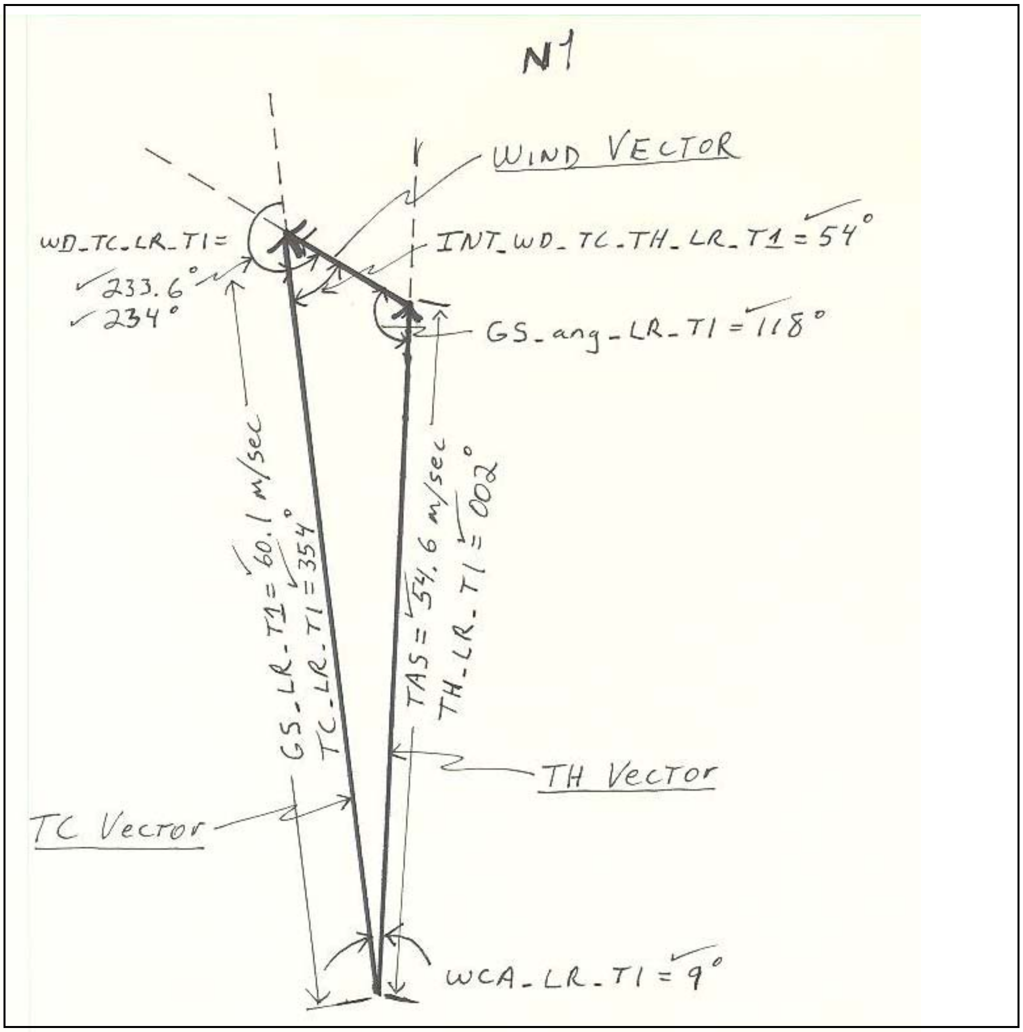

Figure 9. TC-TH-W triangle hand plot example.

15.5 Sgmt_Fuel.m

When the GSs for the route segments are known, time along each one can be computed, and then the fuel consumed. These computations are provided by the subprogram "Sgmt_Fuel.m"; and example of which is shown in the following equations†:

$$\text{Time\_LR\_T1} = \text{DIST\_LR\_T1} / (\text{GS\_LR\_T1} * 3600) = 502{,}508/ (60.1 * 3600) = 2.3 \text{ hr}$$

$$\text{Fuel\_LR\_T1} = \text{Time\_LR\_T1} * \text{Fuel\_consump\_rate\_cruise} = 2.3 * 4.2 \text{ gal-hr}^{-1} = 9.7 \text{ gal}$$

$$\text{Time\_T1\_T2} = \text{DIST\_T1\_T2} / (\text{GS\_T1\_T2} * 3600) = 404{,}479/ (45.1 * 3600) = 2.5 \text{ hr}$$

† The generic formula for the computation of the fuel consumed during flight along a particular route segment is:
Fuel_segment = (DIST_segment * Fuel_consump_rate_cruise) / (GS_segment * 3600)

$$Fuel\_T1\_T2 = Time\_T1\_T2 * Fuel\_consump\_rate\_cruise = 2.5 * 4.2 \text{ gal-hr}^{-1} = 10.5 \text{ gal}$$

$$Time\_T2\_LR = DIST\_T2\_LR / (GS\_T2\_LR * 3600) = 575{,}914 / (54.9 * 3600) = 2.9 \text{ hr}$$

$$Fuel\_T2\_LR = Time\_T2\_LR * Fuel\_consump\_rate\_cruise = 2.9 * 4.2 \text{ gal-hr}^{-1} = 12.2 \text{ gal}$$

15.6 Climb-out Fuel

The fuel burned during initial climb-out is determined in three steps:

(1) Determine the vertical distance to be climbed, which is the difference between the planned initial cruise altitude and the field elevation:

Climb_hgt = cruise_alt - field_elev

Climb_hgt = (4000 – 1358) * 3.28 = 8665.8 ft

(2) Determine the time to climb up to the initial cruise altitude, which is the vertical distance to be climbed divided by the particular UAS rate-of-climb:

Time_climb = climb_hgt / (rate_of_climb)

Time_climb = 8665.8 / (1000 * 60) = .14 hr

(3) The fuel burned during climb-out, which is the time spent during climb-out multiplied by the fuel consumption rate in the climb configuration:

Fuel_climb = Time_climb * Fuel_consupm_rate_climb

Fuel_climb = .14 * 4.4 = 0.6 gal

15.7 Fuel at T1

The fuel required for flight at the primary target area (T1) is determined by multiplying the planned mission-time at T1 by the fuel consumption rate during loitering operations. In this example, 1.5 hrs at T1 is assumed.

Fuel_T1 = Mission_time_T1 * Fuel_consump_rate_loiter

Fuel_T1 = 1.5 * 3.5 = 5.3 gal

15.8 Fuel Reserve

The fuel required to be remaining in reserve when the UAS returns to the LR point is determined by the desired time the vehicle could be orbiting before running out of fuel and having to land. This length of time (Time_resrv) is set by the operator; in this case it is 45 min, which is converted to hours by the FCA.

Fuel_resrv = Time_resrv * Fuel_consump_rate_loiter

Fuel_resrv = 0.75 * 3.5 = 2.6 gal

15.9 Estimated Fuel/Time allowable at T2 using initial forecast winds

The amount of fuel (and therefore time) available at the secondary target area is a function of the total of the other fuel expenditures being subtracted from the initial fuel quantity on-board at take off. In equation form, the T2 fuel is determined by the following:

Fuel_T2 = Fuel_cap – (Fuel_climb + Fuel_LR_T1 + Fuel_T1 +

Fuel_T1_T2 + Fuel_T2_LR + Fuel_resrv)

Fuel_T2 = 49.0 - (0.6 + 9.8 + 5.3 + 10.5 + 12.2 + 2.6) = 8.0 gal

The time available at T2 is found by dividing the T2 fuel by the loitering fuel consumption rate:

Time_at_T2 = 8.0 / 3.5 = 2.3 hrs

16. Summary and Conclusions

A prototype fuel consumption algorithm for UAS has been developed as a MATLAB program. The FCA simulates the fuel requirements for a simple, triangular-shaped UAS mission, and produces a solution for the available fuel and time at a secondary target area.

An extensive test procedure was conducted on the FCA to validate each algorithm output by employing a realistic UAS mission scenario. All intermediate angles, courses, headings, ground speeds, times en route, and quantities of fuel consumed were determined to be correct. Consequently, the allowable time on-station at an alternate target area was accurately calculated.

Plans are underway to contract with an agency outside ARL to enhance the FCAs capabilities and convert the algorithm into the Java programming language. Java code for the FCA is required to enable its eventual implementation into AWRT. Enhancements are needed to allow multiple alternate target areas and frequent input of updated winds aloft. It also may be possible to update the TAS and fuel consumption rates in real-time during a mission given the appropriate UAS aerodynamic relationships and environmental data. In this way the FCA results can be made more accurate than is currently possible, since only default TAS and fuel consumption rates are now being used.

The FCA is ultimately intended to supplement the AWRT by rapidly recalculating UAS fuel requirements as alternate mission routes are derived by the routing tool and as varying winds are encountered in-flight. It is hoped that the FCA will be a valuable addition to the routing tool that will greatly enhance its capabilities and utility for the UAS mission commander.

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Appendix. Complete FCA Test Scenario

A complete FCA test scenario output file was generated and is presented in this appendix. TC_TH_W vector diagrams were prepared (as shown in figure 9) to check each intermediate angle and final output of the subprograms "Wnd_Cor_Ang.m" and "Gnd_Spd.m" for every phase of the FCA's execution (not included herein except for figure 9). The outline numbers shown below (e.g., "3.1" in section A.2 below) correspond to the program execution outline presented in section 14. Much of the material here is contained within the FCA's data output file, although a certain amount of textual material has been added for clarification.

A.1 Mission Parameter Definitions

Las Cruces, NM Airport (LRU) (Launch/Recovery Point – "LR")
UTM_X_LR (m): 319,505
UTM_Y_LR (m): 3,573,455
Field_elev (m ASL): 1358

Navajo Lake, NM Airport (0V1) (Target 1 – "T1")
UTM_X_T1 (m): 263,573
UTM_Y_T1 (m): 4,075,963

Clayton, NM Airport (CAO) (Target 2 – "T2")
UTM_X_T2 (m): 665,828
UTM_Y_T2 (m): 4,033,604

HUNTER RQ-5A UAV PERFORMANCE CHARACTERISTICS

True Air Speed (TAS) (kts):	106
Fuel Capacity (gal):	49.0
Fuel Consumption Rate (climb) (gal/hr):	4.4
Fuel Consumption Rate (cruise) (gal/hr):	4.2
Fuel Consumption Rate (loiter) (gal/hr):	3.5
Rate of Climb (ft/min):	1000
Fuel Reserve (hrs)	0.75
Initial Cruise Altitude (cruise_alt) (m):	4000
Planned Time at T1 (hrs) (Msn_time_T1):	1.5

A.2 Compute Mission-defined Fuel Requirements

3.1 (vertical climb from LR to cruise altitude, ft)
climb_hgt = (cruise_alt - field_elev) * m_ft
climb_hgt (ft) = (4000 – 1358) * 3.28 = 8665.8

(time required to climb to cruise altitude, hr)
Time_climb = climb_hgt / (rate_of_climb*60)
Time_climb (hrs) = 8665.8/(1000 * 60) = 0.14

(fuel required to climb to cruise altitude, gal)
Fuel_climb = Time_climb * Fuel_consump_rate_climb
Fuel_climb (gal) = 0.14 * 4.4 = 0.6

3.2 (fuel required to loiter at T1, gal)
Fuel_T1 = Msn_time_T1 * Fuel_consump_rate_loiter
Fuel_T1 (gal) = 1.5 * 3.5 = 5.3

3.3 (reserve fuel required upon return to LR point, gal)
Fuel_reserve = Time_reserve *Fuel_consump_rate_loiter
Fuel_reserve (gal) = 0.75 * 3.5 = 2.6

A.3 Find True Course Values for Three Route Segments

4.1 (TC and distance from LR to T1)
TC_LR_T1 (deg): 354
DIST_LR_T1 (m): 505,611

4.2 (TC and distance from T1 to T2)
TC_T1_T2 (deg): 096
DIST_T1_T2 (m): 404,479

4.3 (TC and distance from T2 to LR)
TC_T2_LR (deg): 217
DIST_T2_LR (m): 575,914

A.4 First Program Iteration

This iteration of the FCA computes available fuel/time at T2 during the mission planning phase (perhaps 24-48 hrs ahead of the planned launch time), using NWP model forecast wind direction/speed. The operator is prompted to manually input the forecast wind direction/speed.

5.1		
FWD (deg):		120
FWS (kts):		20

Sections 6.1-6.3 and 7.1-7.3 of the program execution outline produce the intermediate angles, WCAs, and THs for the first iteration of the FCA. Section 6.1 indicates the values that have been displayed graphically in figures 8 and 9.

6.1	WD_TC_LR_T1 (deg):	234
	INT_WD_TC_TH_LR_T1 (deg):	54
	WCA_LR_T1 (deg):	9
	TH_LR_T1 (deg):	002
6.2		
	WD_TC_T1_T2 (deg):	24
	INT_WD_TC_TH_T1_T2 (deg):	156
	WCA_T1_T2 (deg):	4
	TH_T1_T2 (deg):	100
6.3		
	WD_TC_T2_LR (deg):	97
	INT_WD_TC_TH_T2_LR (deg):	83
	WCA_T2_LR (deg):	11
	TH_T2_LR (deg):	206
7.1		
	GS_ang_LR_T1 (deg):	118
	GS_LR_T1 (m/s):	60.1
7.2		
	GS_ang_T1_T2 (deg):	20
	GS_T1_T2 (m/s):	45.1
7.3		
	GS_ang_T2_LR (deg):	86
	GS_T2_LR (m/s):	54.9

8.0

Fuel_LR_T1 (gal) = (505611 * 4.2) / (60.1 * 3600) = 9.8
Fuel_T1_T2 (gal) = (404479 * 4.2) / (45.1 * 3600) = 10.5
Fuel_T2_LR (gal) = (575914 * 4.2) / (54.9 * 3600) = 12.2

9.1

Fuel_T2 (gal) = 49.0 – (0.6 + 9.8 + 5.3 + 10.5 + 12.2 + 2.6) = 8.0

The generic equation for computing the time available at T2 is simply the fuel available divided by the fuel consumption rate in the UAS loiter configuration.

9.2

Time_T2 (hrs) = Fuel_T2 / Fuel_consump_rate_loiter
Time_T2 (hrs) = 8.0 / 3.5 = 2.3

A.5 Second Program Iteration

The UAS mission is now in-progress. In-flight GPS-derived winds are known when leaving the LR vicinity (at cruising altitude). This iteration is an update of the expected fuel requirements for the entire mission, assuming that the winds currently being measured will remain constant and apply throughout; although not normally a valid assumption, the winds being input are now at least a measured value during the mission, rather than a forecast from 24-hours (or more) prior‡.

11.0

OWD Launch to T1 (deg):	230
OWS Launch to T1 (kts):	30

12.0

WD_TC_LR_T1 (deg):	124
INT_WD_TC_TH_LR_T1 (deg):	56
WCA_LR_T1 (deg):	14
TH_LR_T1 (deg):	340
WD_TC_T1_T2 (deg):	134
INT_WD_TC_TH_T1_T2 (deg):	46
WCA_T1_T2 (deg):	12
TH_T1_T2 (deg):	108
WD_TC_T2_LR (deg):	13
INT_WD_TC_TH_T2_LR (deg):	167
WCA_T2_LR (deg):	4
TH_T2_LR (deg):	221

‡ Future developments of the FCA could include almost continuous automated input of UAS-measured winds; and so, rapidly updating calculations of fuel usage and availability. The MATLAB prototype, however, requires manual operator input of observed winds as shown in section A.5.(11.0).

13.0

GS_ang_LR_T1 (deg): 110
GS_LR_T1 (m/s): 62.0

GS_ang_T1_T2 (deg): 122
GS_T1_T2 (m/s): 64.0

GS_ang_T2_LR (deg): 9
GS_T2_LR (m/s): 39.0

14.0

Fuel_LR_T1 (gal) = (505611 * 4.2) / (62.0 * 3600) = 9.5
Fuel_T1_T2 (gal) = (404479 * 4.2) / (64.0 * 3600) = 7.4
Fuel_T2_LR (gal) = (575914 * 4.2) / (39.0 * 3600) = 17.2

15.0

Fuel_T2 (gal) = 49.0 – (0.6 + 9.5 + 5.3 + 7.4 + 17.2 + 2.6) = 6.4

Time_T2 (hrs) = Fuel_T2 / Fuel_consump_rate_loiter
Time_T2 (hrs) = 6.4 / 3.5 = 1.8

A.6 Third Program Iteration

The UAS mission is now assumed to be leaving Target Area 1 (T1) en route to an alternate target (T2). Updated GPS winds are known when leaving T1. This iteration is an update of the expected fuel requirements for the remainder of the mission, assuming that the winds currently being measured will remain constant and apply for the route segment from T1 to T2, and for the segment from T2 back to the LR point. Also, at this point in the flight, the *actual* time expended traveling from LR to T1 and the *actual* time spent loitering at T1 are known, so more accurate estimates of fuel consumed thus far are possible[§].

17.0

Actual_Time_LR_T1 (hrs): 2.5
Actual_Time_T1 (hrs): 2.0

17.1

The actual fuel used en route from LR to T1 is the actual time en route multiplied by the cruise fuel consumption rate. The actual fuel expended at T1 is the actual time at T1 multiplied by the loitering fuel consumption rate.

Actual_Fuel_LR_T1 (gal) = 2.5 * 4.2: 10.5
Actual_Fuel_T1 (gal) = 2.0 * 3.5: 7.0

[§] Although future versions of the FCA may include an automated calculation of the actual times en route to T1 and at T1, the MATLAB prototype requires a manual operator input.

18.0

OWD Leaving T1 (deg):	340
OWS Leaving T1 (kts):	40

19.0

WD_TC_T1_T2 (deg):	244
INT_WD_TC_TH_T1_T2 (deg):	64
WCA_T1_T2 (deg):	20
TH_T1_T2 (deg):	76
WD_TC_T2_LR (deg):	123
INT_WD_TC_TH_T2_LR (deg):	57
WCA_T2_LR (deg):	18
TH_T2_LR (deg):	235

20.0

GS_ang_T1_T2 (deg):	96
GS_T1_T2 (m/s):	60.0
GS_ang_T2_LR (deg):	105
GS_T2_LR (m/s):	63.0

Note: The two remaining T2 fuel/time calculations will include the *actual* fuel usage from LR to T1 and at T1, as derived above.

Actual_Fuel_LR_T1 (gal):	10.5
Actual_Fuel_T1 (gal):	7.0

21.0

Fuel_T1_T2 (gal) = (404479 * 4.2) / (60.0 * 3600) =	7.9
Fuel_T2_LR (gal) = (575914 * 4.2) / (63.0 * 3600) =	10.7

22.0

Fuel_T2 (gal) = 49.0 – (0.6 + 10.5 + 7.0 + 7.9 + 10.7 + 2.6) = 9.7

Time_T2 (hrs) = Fuel_T2 / Fuel_consump_rate_loiter	
Time_T2 (hrs) = 9.7 / 3.5 =	2.8

A.7 Fourth Program Iteration:

The UAS mission is now arriving at T2 and updated GPS-derived winds are known. This iteration is an update of the expected fuel requirements for the remainder of the mission, assuming that the winds currently being measured at T2 will remain constant and apply for the route segment from T2 back to the LR point. At this point in the flight, the *actual* time expended traveling from T1 to T2 is known and is input manually. Therefore, more accurate estimates of fuel consumed thus far are possible.

24.0

Actual_Time_T1_T2 (hrs): 1.6

24.1

Actual_Fuel_T1_T2 (gal) = 1.6 * 4.2: 6.7

25.0

OWD Arriving at T2 (deg): 045

OWS Arriving at T2 (kts): 45

26.0

WD_TC_T2_LR (deg): 172

INT_WD_TC_TH_T2_LR (deg): 8

WCA_T2_LR (deg): 3

TH_T2_LR (deg): 214

27.0

GS_ang_T2_LR (deg): 169

GS_T2_LR (m/s): 78.0

28.0

Fuel_T2_LR (gal) = (575914 * 4.2) / (78.0 * 3600) = 8.6

29.0

Fuel_T2 (gal) = 49.0 – (0.6 + 10.5 + 7.0 + 6.7 + 8.6 + 2.6) = 13.0

Time_T2 (hrs) = Fuel_T2 / Fuel_consump_rate_loiter

Time_T2 (hrs) = 13.0 / 3.5 = 3.7

List of Symbols, Abbreviations, and Acronyms

A*	A-Star
ARL-BE	Army Research Laboratory, Battlefield Environment Division
AWRT	Aviation Weather Routing Tool
DWD	Down Wind Direction
FCA	Fuel Consumption Algorithm
FWD/FWS	forecast wind direction/speed
GPS	Global Positioning System
GS	Ground Speed
lat/lon	latitude/longitude
LR	launch/recovery point
MC	mission commander
NM	New Mexico
NWP	Numerical Weather Prediction
OWD/OWS	observed wind direction/speed
Supp_Ang	Supplementary Angle
TC	True Course
TH	True Heading
TAS	True Airspeed
UAS	Unmanned Aircraft Systems
UTM	Universal Transverse Mercator
W	Wind Vector
WCA	Wind Correction Angle

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